Micro-CT Study of the *In Vivo* Accuracy of a Wireless Electronic Apex Locator

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SIGNIFICANCE

Success or failure of endodontic treatment depends, among other parameters, on an accurate determination of the working length (WL) as demonstrated by clinical evidence.

ABSTRACT

Introduction: This study aimed to compare the *in vivo* accuracy of Wirele-X and RootZX II electronic apex locators (EALs) in determining the position of the major foramen using micro–computed tomography (micro-CT) as the analytical tool. **Methods:** Eleven vital teeth planned for extraction from 5 patients were used. After conventional access cavity preparation, root canals were flared and negotiated up to the apical third with sizes 08 and 10 K-files followed by irrigation with 2.5% NaOCl. K-type files were used to determine the working length of the selected canals using Root ZX II and Wirele-X apex locators until their numeric displays read "0.0." After fixing the silicon stop to the file, teeth were extracted and imaged in a micro-CT device using a double-scan protocol. Image stacks, with and without the file in the root canal, were then co-registered and the measurement error calculated as the absolute difference between the tip of the file and the major foramen. Positive and negative values were recorded when the file tip was detected beyond or short of the major foramen, respectively. Accuracy was determined on stable measurements within ± 0.5 mm when the file tip did not extend beyond the major foramen. The χ^2 test was applied to compare the ability of the EALs to detect the position of the major foramen, and the *t* test for dependent variables was used to verify differences in the 2 measurements obtained in each tooth. Significance level was set at 5%. **Results:** Within a tolerance level of ± 0.5 mm, no significant differences were observed between the tested EALs regarding the absolute distance values ($P = .82$) or in their ability to detect the position of the major foramen ($\chi^2 = 0.2588$; $P = .6109$). The accuracy of the Root ZX II and the Wirele-X apex locators within ± 0.5 mm were 81.8% and 90.9%, respectively. **Conclusions:** Root ZX II and Wirele-X performed similarly regarding the *in vivo* detection of the major foramen. Using strict criteria, the accuracy of the Root ZX II and the Wirele-X apex locators were 81.8% and 90.9%, respectively. *(J Endod 2022;48:1152–1160.)*

KEY WORDS

Apex; apical foramen; electronic apex locator; micro-CT; working length

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Success or failure of endodontic treatment depends on the accurate determination of the working length[1] (WL), which has been defined as the distance from a coronal reference point to the point at which canal preparation and filling should terminate[2]. Historically, several methods have been used to determine the WL, such as radiographic examination and the patient response to pain, caused by passing of the instrument through the apical foramen[3]. Undoubtably, the advent of electronic apex locators (EALs) provided an additional feature to the endodontic arsenal, overcoming the intrinsic disadvantages of the radiographic method[4], while reducing the treatment time and the radiation dose to the patient[3–5]. Nowadays, a high level of precision and accuracy are important requirements of EALs to effectively determine the WL. Although precision (also reported as consistency, repeatability, reproducibility, or reliability) is how much subsequent determinations of the endpoint of the same canal with the same EAL differ from each other, accuracy is the ability of the EAL to locate the true endpoint of the canal[5]. In an *in vivo* study in which the accuracy of 2 EALs in determining the WL in 482 canals was compared with the radiographic method[6], the authors concluded that all electronic measurements

were within ± 0.5 mm of the minor foramen while, at this same range, radiographic exams were accurate in only 15% of the cases.

The recently launched Wirele-X apex locator (Forumtec, Ashkelon, Israel) is a wireless device that aims to extend the functional possibilities of EALs available on the market. According to the manufacturer, several new features were implemented in this EAL to ensure better precision and control (https://www.forumtec.net/products-apexlocators/). In contrast to other EALs that use mixed frequencies, measurements with the Wirele-X device are performed using alternating current signals at 2 alternated frequencies, cancelling the need for signal filtering and eliminating noise caused by nonideal filters. Moreover, the patented-based signal measuring method calculates the position of the file by the Root Mean Square and not signal amplitude or phase. This value represents the energy level of the signal and is more immune to various kinds of electromagnetic noises then other parameters of the measured signal. In addition, proprietary software algorithms are used to calculate the movement of the file in the root canal, offering a real time presentation of its position through a high-resolution color graphic display.

Many studies have pointed out the advantages, disadvantages, precision, and accuracy of different EALs. These assessments have been made both *in vivo* and *in vitro* and almost all of them used direct visual measurements of the distance from the file tip to some anatomic landmark at the apical canal by using scanning electron microscopy[7], stereomicroscopy[8], or radiography[9], with or without grinding the apical root. In other studies, the root structure was preserved and accuracy was determined by measuring the distance from the file tip to a silicone stop previously adjusted to the coronal surface of the tooth after determining the canal length by visualizing the tip of the file at the apical foramen[10]. Although these methods have been successfully used for decades, none of them allowed for a detailed 3-dimensional (3D) analysis of the relationship between the tip of the file and the anatomic structures of the apical canal, an approach possible to be accomplished using high-resolution nondestructive micro-CT technology. In 2016, Piaseck et al[11] used a micro-CT device to evaluate the accuracy of 2 EALs and concluded that the 0.5 mark could be used to properly determine the WL, whereas some anatomic variations of the root canal at the apical third could influence their accuracy. Later, this same group used micro-CT to compare 3 EALs set at 0.0 and 0.5 marks in curved mesial canals of extracted mandibular molars and reported that Root ZX Mini (J Morita, Tokyo, Japan) and CanalPro (ColteneEndo, Cuyahoga Falls, OH) were precise in both marks, whereas the accuracy of Apex ID (SybronEndo, Glendora, CA) was higher at the 0.5 mark[12]. In this same year, Connert et al[13] used micro-CT to evaluate the accuracy of 9 EALs in 91 root canals by measuring the distances from the file tip to the apical constriction and major foramen. The authors concluded that using EALs to determine the major foramen led to an overestimation of the WL, recommending the use of EAL scale at the constriction level. More recently, Suguro et al[14] compared the accuracy of 2 EALs in extracted teeth using micro-CT and reported that the apical foramen was located in 80% to 90% of the samples with a tolerance level of ± 0.5 mm. Notwithstanding the successful application of a precise 3D analytical method to study the accuracy of EALs, the results of these studies[11–14] clearly demonstrate that this topic is still embroiled in controversies.

Independent of the capability of an EAL to locate a certain morphologic landmark or area, the physiologic foramen (0.0 display mark) is the anatomic landmark that clinicians always attempt to determine at the first stages of the root canal treatment[15]. According to Piasecki et al[12], mean lengths obtained by using the 0.0 mark of the EAL are very close to the actual root canal length. Considering the lack of literature information, the present study aimed to compare the *in vivo* accuracy of the Wirele-X and the benchmark RootZX II (J Morita) apex locators, set at the 0.0 display mark, in determining the position of the apical foramen in different teeth by comparing the electronic measurements with micro-CT images. The null hypothesis tested was that there is no difference between the Wirele-X and the RootZX II in determining the location of the apical foramen in an *in vivo* condition.

MATERIAL AND METHODS

Sample Size Calculation

The minimal sample size for this study has been estimated using the G*Power 3.1 for Mac relying on a *t* test family for 2 dependent means. The effect size input (1.6) has been obtained from the results by Welk et al[16] with an alpha error of 0.05 and power beta of 0.95. The results indicated a minimal sample size of 8 teeth to observe significant differences between the groups.

Sample Selection

Five healthy adult patients referred for the extraction of 11 teeth due to periodontal or prosthodontic reasons participated in this study. Informed consent was obtained before treatment under a study protocol approved by the local research ethical committee (protocol 40352320.9.0000.5243). A preoperative periapical radiograph was taken using a digital sensor 5100 (Carestream Dental, Atlanta, GA) confirming that all experimental teeth had fully formed root apices, visible canals, no fracture, no resorption, no previous endodontic treatment, and adequate remaining tooth structure for rubber dam isolation. Pulp sensibility was assessed using Endo-Ice refrigerant spray (Hygenic Corp., Akron, OH) and recorded as either vital or necrotic after the pulp was accessed and vascular status determined. Only vital teeth were included in this study. The gender and age of the patients, the identification of the experimental teeth, and the selected canals of molars are depicted in Table 1.

Experimental Procedures

All teeth were treated under magnification by an operator with 15 years of clinical experience (V.B.C.F). After administration of local anaesthesia and isolation under rubber dam, existing caries and/or restorations were removed. The incisal edges and cusps were flattened with a cylindrical diamond bur using a high-speed handpiece under water irrigation to establish a level surface to serve as a stable reference for all measurements. After conventional access cavity preparation, the pulp chamber was irrigated with 2.5% sodium hypochlorite (NaOCl) for 1 min, and the coronal portion of the selected canal was flared using a Gates-Glidden drill size 2 (Dentsply Maillefer, Ballaigues, Switzerland). Then, the root canal was negotiated up to the apical third with sizes 08 and 10 K-files (Dentsply Maillefer), rinsed with 2.5% NaOCl, and the pulp chamber filled with the irrigant solution. Excess fluid was removed from the pulp chamber with cotton pellets and the WL of the canal was determined using 2 EALs: Root ZX II and Wirele-X. In each tooth, the order of EALs use was randomly assigned with a flip of a coin. The lip clip of the first selected EAL was then attached to the patient's lip and a stainless-steel K-file was connected to the electrode of the apex locator. All of measurements were made with the first file to bind at the WL (Table 1). The file was gently inserted into the root canal until the numeric display of the apex locator reads "0.0." This indicates the location of the major foramen according to the manufacturer's instructions. All measurements were considered to be valid if the reading/signal on screen remained stable

TABLE 1 - Demographic factors of patients and K-file size used for working length determination in each experimental tooth.

Donor	Gender	Age	Teeth	Root Canal	K-File
1	F	41	42	—	10
			42		10
			31		10
2	F	59	12	—	20
3	M	54	42	—	10
			41	—	10
			32	—	10
			31	—	10
4	F	51	16	Palatal	15
			17	Palatal	15
5	M	56	42	—	20

—, does not apply, single root canal.

for at least 5 seconds. The silicon stop was then adjusted to the reference plateau created on the external surface of the crown. The WL was electronically rechecked to confirm the file position and the silicon stop was glued to the file with a synthetic adhesive composed of cyanoacrylate ester (Super Bonder, Henkel, Germany). After that, the file was withdrawn from the tooth, and a digital calliper (Mitutoyo, Tokyo, Japan) was used to measure the length between the tip of the instrument and the silicon stop to the nearest 0.01 mm. These procedures were repeated in the same canal with the second EAL using a different file with the same size. Teeth were then extracted and stored in distilled water.

Micro-CT Scanning and Analyses

Teeth were slightly dried and scanned in a micro-CT device (SkyScan 1173; Bruker-microCT, Kontich, Belgium) at a pixel size of 9.34 μm or 11.14 μm (according to the size of the tooth), frame average of 5, filtered with a 1.0-mm-thick aluminium plate, with (90 kV, 88 mA, 360° rotation with steps of 0.3°) and without (70 kV, 114 mA, 360° rotation with steps of 0.5°) the instrument inserted into the root canal space. Image reconstruction was performed using standard parameters for ring artifact correction (4) and beam hardening correction (40%), and contrast limits varied from 0.0 to 0.12 (with the instrument) and from 0.0 to 0.05 (without the instrument), resulting in 900 to 1200 grayscale cross-section images per tooth (NRecon v.1.7.16 software; Bruker-microCT). Then, image stacks without the instrument were co-registered to their respective datasets with the instrument within the root canal using the 3D Slicer 4.6.0 software (available at https://www.slicer.org/) aiming to visualize the dentin without the metal artifact created by the alloy. For each reading, the measurement error was calculated as the absolute difference, in millimeters, between the tip of the instrument and a tangent line crossing the margins of the major foramen (Figs. 1 and 2). Positive and negative values were recorded when the tip was detected beyond or short of the tangent line, respectively, using FIJI/ImageJ (Fiji v.1.51n; Fiji, Madison, WI) software. Accuracy was determined on stable measurements within ± 0.5 mm, excluding the ones extending beyond the apical foramen.

Statistical Analyses

The distances from the file tip to the tangent line were calculated for both groups and categorized in intervals of 0.05 mm into 4 groups. The frequency distribution of samples at each category was then calculated and the χ^2 test applied to verify differences between the tested EAL. The absolute distance values were also compared using a *t* test for dependent variables to verify the dissonances of the 2 measurements obtained in each tooth. Significance level was set at 5% (SPSS v.25; SPSS Inc., Chicago, IL).

RESULTS

The frequency distributions of the distances measured by both EALs are depicted in Table 2. Within a tolerance level of ± 0.5 mm, no significant differences were observed between the tested EALs regarding the absolute distance values ($P = .82$) or in their ability to detect the position of the major foramen ($\chi^2 = 0.2588$; $P = .6109$). The accuracy of the Root ZX II and the Wirele-X apex locators within ± 0.5 mm were 81.8% and 90.9%, respectively, excluding measurements obtained beyond the major foramen. Figure 3 illustrates the distances measured from the file tip to the tangent line in the selected canals.

DISCUSSION

The present *in vivo* study was undertaken to compare the accuracy of a wireless apex locator (Wirele-X) with the well-known Root ZX II in detecting the position of the major foramen. This is the first research in which a wireless EAL was tested in patients and its accuracy was verified through the nondestructive micro-CT technology. Consequently, our findings cannot be directly compared with the literature. Within a tolerance level of ± 0.5 mm, results showed no difference in the ability of Wirele-X and Root ZX II apex locators to detect the position of the major foramen (Table 2), and the null hypothesis was accepted. In this study, however, none of the tested EALs were able to precisely detect the position of the major foramen and, in 3 (27.2%) and 2 (18.2%) specimens of the Root ZX II and Wirele-X groups, respectively, the tips of the files were located outside the root canal space. These findings are corroborated by other authors that tested the Root ZX and reported the extension of the file tip beyond the major foramen in 40%[17], 32.1%[18], 30.8%[19], 26%[20], and 16.7%[21] of the samples. Because of that, in the present study, when a strict clinical tolerance limit was applied, the obtained accuracies of the Root ZX II and the Wirele-X apex locators were 81.8% and 90.9%, respectively. These findings suggest that, in a clinical setup, WL determination with these EALs using the 0.0 mark would require an adjustment of the file to keep it within the limits of the root canal space.

In the literature, several *in vivo* studies have tested the accuracy of the Root ZX in different groups of teeth (Table 3). In this type of study, electronic and/or radiographic WL determination is performed before tooth extraction and the confirmation of the actual WL is confirmed after extraction. Overall, when measurements are performed at the 0.5 display mark of the EALs, a wide range of accuracies were reported (46.4% to 99.8%) within ± 0.5 mm from the WL, possibly because of differences in the experimental conditions and methods of analysis. On the other hand, although some *in vivo* studies also used the 0.0 display mark[5,7,22,23] as in the current research, only Pagavino et al[7] reported the *in vivo* accuracy of the Root ZX (Table 3), which was similar (82.75%) to our findings (81.8%). Some authors have suggested that the 0.0 and 0.5 display marks of the EALs can be used indistinctly because no statistical difference was observed in the WL

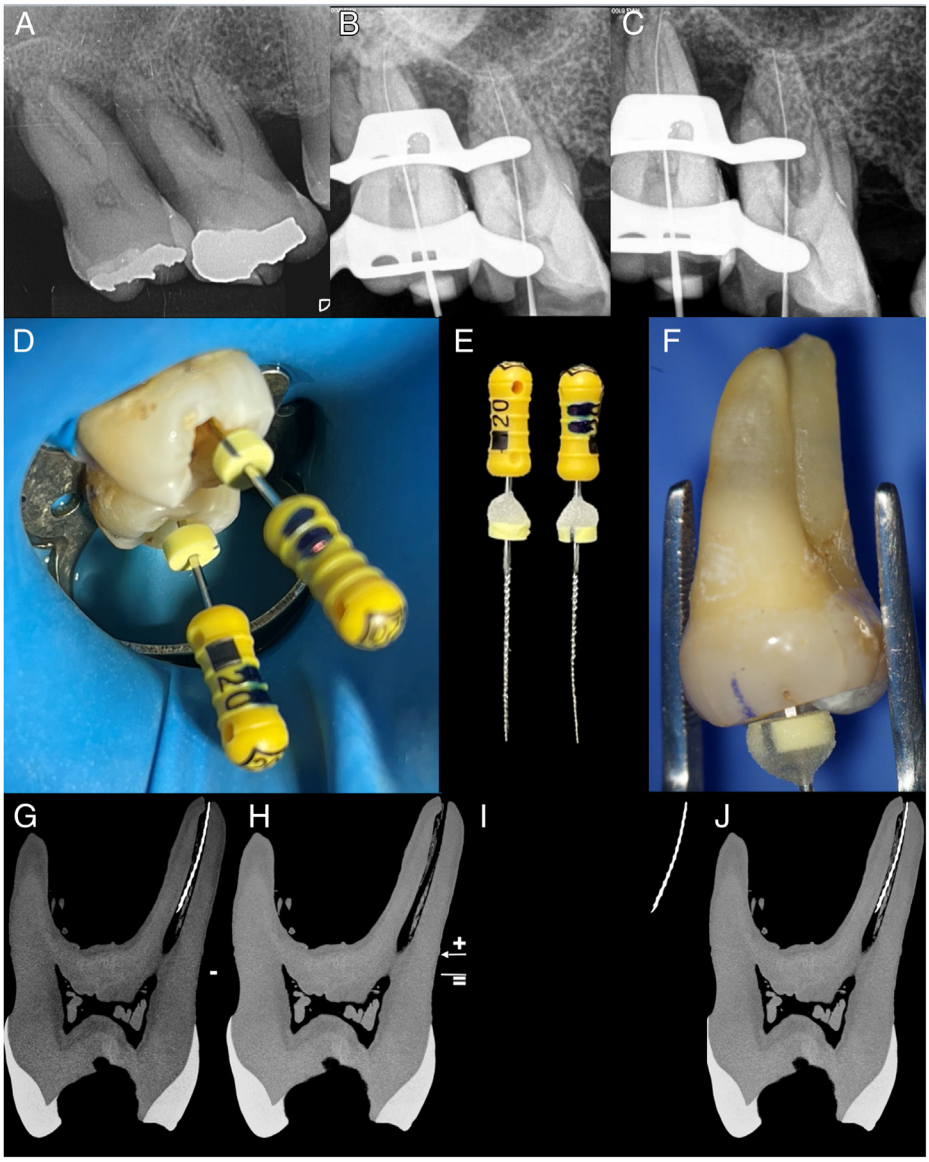

FIGURE 1 – (*A*) Preoperative periapical radiographs. (*B, C*) Transoperative radiographs showing the files at the position when the numeric display of the apex locator reads "0.0." (*D*) Silicon stops were adjusted to the reference plateau created on the external surface of the crown. (*E*) Silicon stops were glued to the file with a synthetic adhesive composed of cyanoacrylate ester when the numeric display of the apex locator reads "0.0." A digital calliper (Mitutoyo, Tokyo, Japan) was used to measure the length between the tip of the instrument and the silicon stop to the nearest 0.01 mm. (*F*) The instrument was inserted into the root canal space for the scanning procedure. (*G–J*) Micro–computed tomography images demonstrating the precise location of the file tip position in relation to the apex after reduction of artifacts produced by the alloy with the use of a double-scan protocol.

determination with both of them[5,24]. Although some manufacturers claim that these display marks locate the apical constriction and the major foramen, respectively, in fact they have been considered as arbitrary indicators of the more coronal or apical position of the file in the space between the apical constriction and apical foramen rather than of the exact location of these anatomic landmarks[5]. This statement is supported by the present findings (Fig. 3) and also by Connert et al[13] who compared the accuracy of 9 EALs in extracted teeth using micro-CT. Therefore, considering the limitation of EALs in locating the exact position of anatomic landmarks of the root canal, some authors suggested using the 0.0 display mark, as this allows for more accurate results[5,25]. In fact, the major foramen (0.0 display mark of the EAL) was chosen as the reference point in this study not only because its position can be consistently reproduced, rather than that of the minor foramen[21,26–29], but also because of the possibility of being easily identified in the acquired images. In addition, this study established the tolerance range at ± 0.5 mm from the apical foramen because this margin of error has been considered as an acceptable clinical limit of agreement for WL measurements made by EALs in most *in vivo* studies (Table 3).

In *in vivo* studies, destructive (grinding, clearing) and 2-dimensional (radiograph, calliper) methods have been the most commonly used procedures to evaluate the accuracy of the Root ZX after tooth extraction (Table 3). In the present study, micro-CT technology was chosen as the analytical tool because of the possibility of performing a 3D and nondestructive evaluation of the specimens. The double-scan protocol applied to the analysis allowed the reduction of artifacts produced by the alloy of instruments

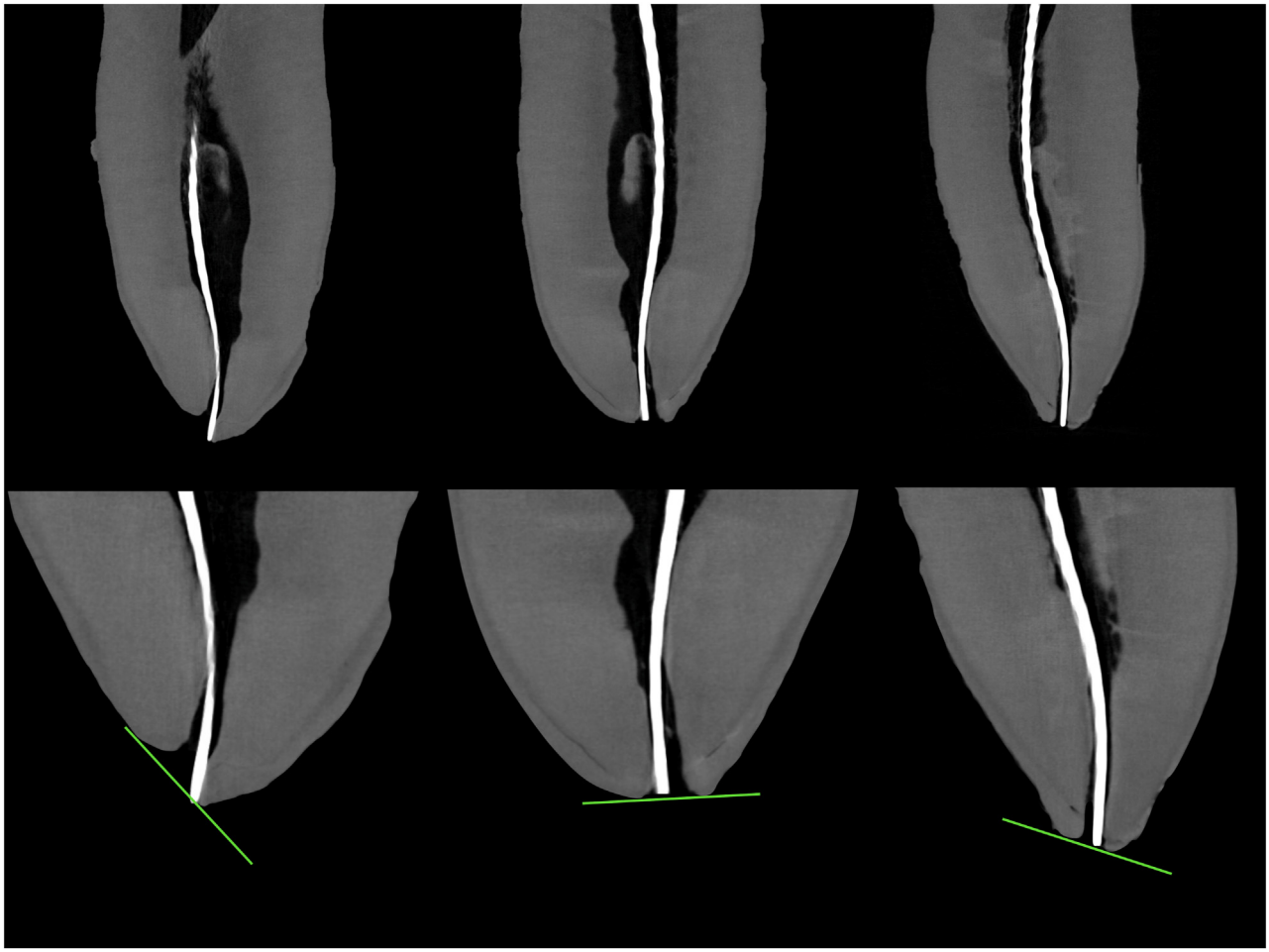

FIGURE 2 – Longitudinal micro–computed tomography cross-sections of the apical third showing the tip of an endodontic file positioned at the "zero" reading mark of the numeric display of the electronic apex locator indicating the position of the major foramen.

on dentin, enabling the precise location of the file tip position in relation to the apex (Fig. 1). Although micro-CT had been used to evaluate the electronic determination of WL in other studies[11–14], this is the first paper in which this methodological approach was applied to validate the accuracy of EALs after being used in patients. However, notwithstanding the clear advantages of micro-CT compared with conventional approaches, this type of study is costly and time-consuming. Besides, it is difficult to obtain a large number of similar teeth to conduct a series of measurements with different EALs and instrument sizes under different root canal environments because of economic and bioethical reasons[15], and this is one of the limitations of this study. On the other hand, attempts were made to reduce procedural errors by having the same operator assigning a random order to the EALs and performing the WL measurements in patients, while another operator, blinded to the used EAL, was responsible for conducting the analysis using micro-CT imaging.

In the past decades, technological advancements allowed the development of a large number of electronic gadgets aiming to improve the quality of root canal treatment. The EAL is possibly one of the most important devices of the endodontic armamentarium once it eliminates many of the problems associated with traditional radiographic methods. Throughout the years, EALs evolved from less accurate resistance-based apparatus to a new generation of precise multifrequency devices. The principle behind multiple-frequency EALs is based on the change in impedance of the file to tissue fluids. When the tip of the file is located away from the minor diameter of the canal, the impedance in the canal is negligible, but when the file reaches its vicinity, the magnitude of the impedance suddenly increases[30]. As the

TABLE 2 - Frequency Distribution of the Distance from the File Tip to the Foramen Obtained from Measuring 11 Root Canals *In Vivo* Using Root ZX II and Wirele-X Apex Locators

	Root ZX II		Wirele-X	
Distance (mm)	***n***	**%**	***n***	**%**
−1.0 to −0.5	—	—	—	—
−0.5 to 0.0	8	72.7	9	81.8
0.1 to 0.5	3	27.3	2	18.2
0.5 to 1.0	—	—	—	—

—, does not apply, single root canal.

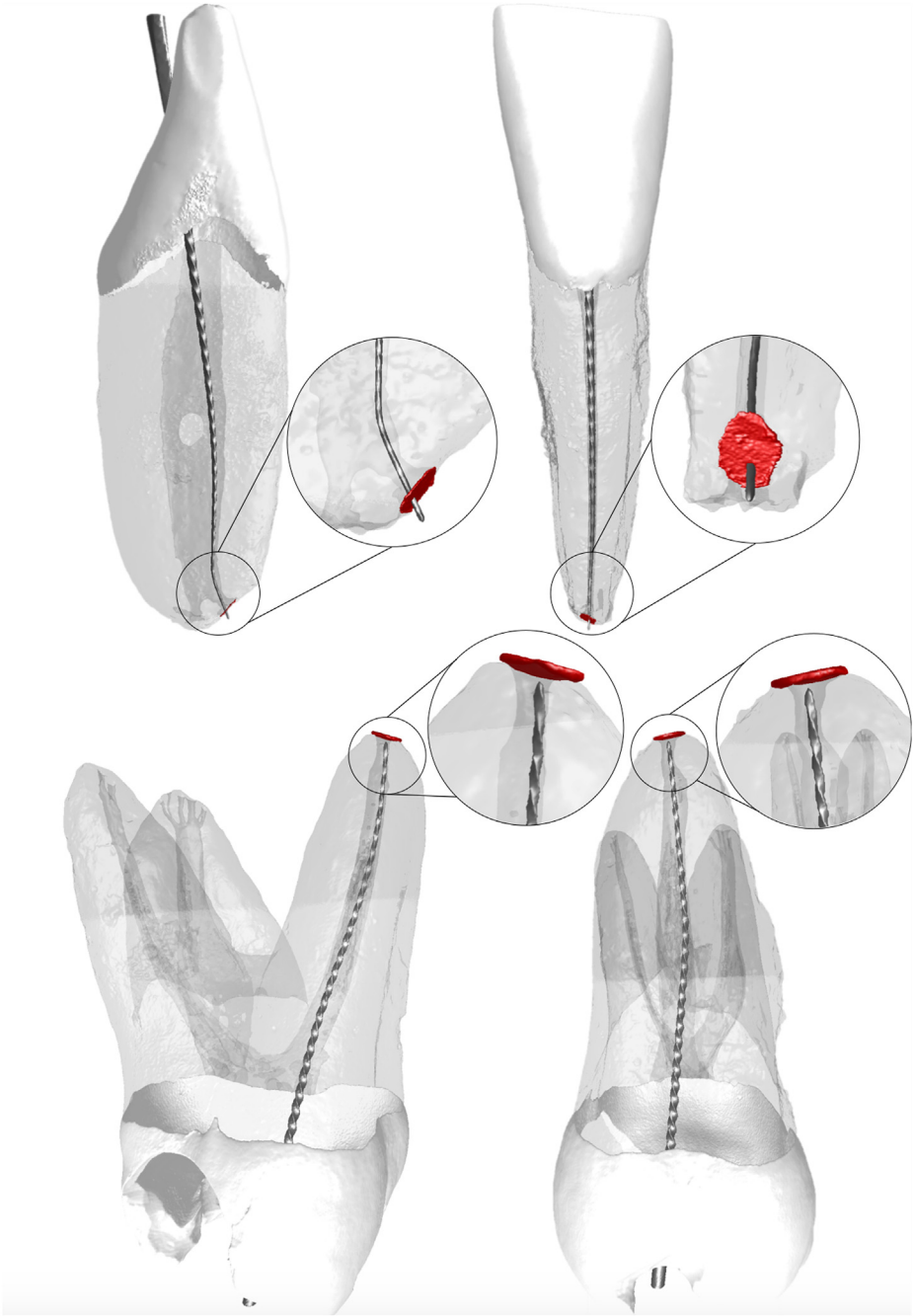

FIGURE 3 – Three-dimensional micro–computed tomography models illustrating the distances from the file tip to the tangent line at the major foramen measured by the tested electronic apex locators. The accuracy of the Root ZX II and the Wirele-X apex locators within ± 0.5 mm were 81.8% and 90.9%, respectively.

file tip contacts the periapical tissue the impedance value rapidly decreases, indicating that the file is beyond the minor diameter of the canal[16]. Whereas Root ZX II uses 2 different electric current frequencies (0.4 and 8 kHz), measurements with Wirele-X uses alternating current signals at 2 alternated frequencies. Although the manufacturer claims that its patented-based signal measuring method increases its precision by cancelling the need for signal filtering, as it eliminates noise caused by nonideal filters, no statistical difference was observed on its accuracy compared with the Root ZX II (Table 2).

The results of the present *in vivo* study confirm previous findings that demonstrate that EALs can accurately determine the canal length to within 0.5 mm from the major foramen (Table 3); however, in this study, only vital teeth were selected. Although some *in vivo* studies found no significant influence of pulp and periapical status on the accuracy of different EALs[20,31–33], they also reported larger standard deviation values and overestimated measurements in necrotic teeth. This is an important aspect to be

TABLE 3 - Summary of *in vivo* studies on the accuracy of Root ZX or Root ZX II.

Authors	Number of patients (teeth)	Tooth type	Pulp status	Irrigant solution	Tested EALs	Display mark	Analytical methods	Tolerance limit	Root ZX accuracy
Adorno *et al.* 2021	43 (43)	Maxillary anterior teeth	Irreversible pulpitis Necrotic	2.5% NaOCl	Root ZX II RomiApex	0.0	Digital calliper	± 0.5 mm	N.R.
Dunlap *et al.* 1998	15 (29)	N.R.	Vital Necrotic	2.5% NaOCl	Root ZX	0.5	Grinding	± 0.25 mm ± 0.5 mm ± 0.75 mm	52.9% 82.3% 94.1%
Duran-Sindreu *et al.* 2012	N.R. (21)	Incisor, canine, and premolar	Vital	4% NaOCl	Root ZX	0.5	Grinding	± 0.5 mm ± 1.0 mm	78.3% 100%
Duran-Sindreu *et al.* 2013	14 (28)	Single-rooted	Vital	2.5% NaOCl or 2% chlorhexidine	Root ZX iPex	0.5	Digital calliper	± 0.5 mm ± 1.0 mm	46.4% 82.1%
Kim *et al.* 2008	N.R. (25)	Premolar	Vital	N.R.	Root ZX	0.5	Stereomicroscope Grinding	± 0.5 mm	84%
Orosco *et al.* 2011	22 (N.R.)	Maxillary incisors and canines	Vital Necrotic	1% NaOCl	Root ZX	0.0 (-1 mm)	Radiograph	N.R.	N.R.
Pagavino *et al.* 1998	19 (35)	N.R.	Vital	2.5% NaOCl	Root ZX	0.0	SEM	± 0.5 mm	82.75%
Shabahang *et al.* 2006	7 (26)	N.R.	Vital	N.R.	Root ZX	0.5	Clearing	± 0.5 mm	96.2%
Stöber *et al.* 2011	N.R. (37)	Incisor, canine, and premolar	N.R.	4% NaOCl	Root ZX iPex	0.5	Grinding SEM	± 0.5 mm ± 1.0 mm	72% 100%
Welk *et al.* 2003	7 (32)	Incisor, canine, and premolar	N.R.	2.6% NaOCl	Root ZX AFA 8005	0.5	Grinding	± 0.5 mm	90.7%
Williams *et al.* 2006	11 (15)	Incisor, premolar, molar	N.R.	5.25% NaOCl	Root ZX	0.0	Grinding	± 0.25 mm	N.R.
Wrbas *et al.* 2006	15 (20)	Single-rooted	N.R.	1% NaOCl	Root ZX Raypex 5	0.5	Grinding	± 0.5 mm	75%

N.R., not reported; SEM, scanning electron microscopy

considered mostly because laboratory and clinical reports also demonstrated that the disruption of the apical anatomy in necrotic cases might affect the accuracy of EALs[5,18,34,35]. Therefore, it may be suggested that further *in vivo* and/or *ex vivo* studies aimed to compare the accuracy of recently launched wireless devices with conventional EALs and try to correlate the results with the diameter of the major foramen in teeth presenting different pulp and periapical status, using the methodological approach suggested herein.

CONCLUSIONS

Within the tolerance level of ± 0.5 mm, Root ZX II and Wirele-X performed similarly regarding the *in vivo* detection of the major foramen. Using strict criteria, the accuracy of the Root ZX II and the Wirele-X apex locators were 81.8% and 90.9%, respectively.

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